

Dilepton production in the strongly interacting quark-gluon plasma

O. Linnyk,^{a,*} W. Cassing,^b E. L. Bratkovskaya,^{a,c} J. Manninen^b

^a Institut für Theoretische Physik, Universität Frankfurt am Main, 60438 Frankfurt am Main, Germany

^b Institut für Theoretische Physik, Universität Giessen, 35392 Giessen, Germany

^c Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany

Abstract

Dilepton production in relativistic heavy-ion collisions is studied within the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach, which is based on a dynamical quasiparticle model (DQPM) matched to reproduce lattice QCD results in thermodynamic equilibrium. A comparison to the data of the NA60 Collaboration for $In + In$ collisions at 158 A·GeV shows that the dilepton spectra are well described by the sum of hadronic and partonic sources, if a collisional broadening of vector mesons is taken into account as well as the off-shell quark-antiquark annihilation ($q + \bar{q} \rightarrow l^+ l^-$ and $q + \bar{q} \rightarrow l^+ l^- g$) in the QGP. In particular, the observed softening of the m_T spectra at intermediate masses is reproduced. The data of the PHENIX collaboration on dilepton production in $Au + Au$ collisions at $\sqrt{s} = 200$ GeV for masses above 1 GeV are found to be dominated by the contributions of the QGP radiation and the charm meson decays, while the measured spectrum is underestimated in the mass range from 0.2 to 0.6 GeV.

Keywords: Relativistic heavy-ion collisions, Meson production, Quark-gluon plasma

1. Introduction

Dileptons are emitted over the entire space-time evolution of the heavy-ion collision, from the initial nucleon-nucleon collisions through the hot and dense phase and to the hadron decays after the freeze-out. This is both a challenge and advantage of the probe. The separation of different “physics” in the dilepton radiation is nontrivial due to the nonequilibrium nature of the heavy-ion reactions and covariant transport models have to be used to disentangle the various sources that contribute to the final dilepton spectra seen experimentally.

To address the dilepton production in a hot and dense medium – as created in heavy-ion collisions – we employ an up-to-date relativistic transport model, i.e. the Parton Hadron String Dynamics [1] (PHSD). The PHSD transport approach describes the non-equilibrium evolution of relativistic heavy-ion collisions: from the initial hard scatterings to the partonic phase in the early hot reaction region followed by hadronization and off-shell hadron propagation and interactions. Within PHSD, one solves generalized transport equations on the basis of the off-shell Kadanoff-Baym equations for Greens functions in phase-space representation (in a first order gradient expansion beyond the quasiparticle approximation).

The description of partons in PHSD is based on the dynamical quasiparticle model (DQPM) matched to reproduce lattice QCD results in thermodynamic equilibrium [2]. According to the DQPM the constituents of the strongly

*corresponding author

Email address: linnyk@fias.uni-frankfurt.de (O. Linnyk.)

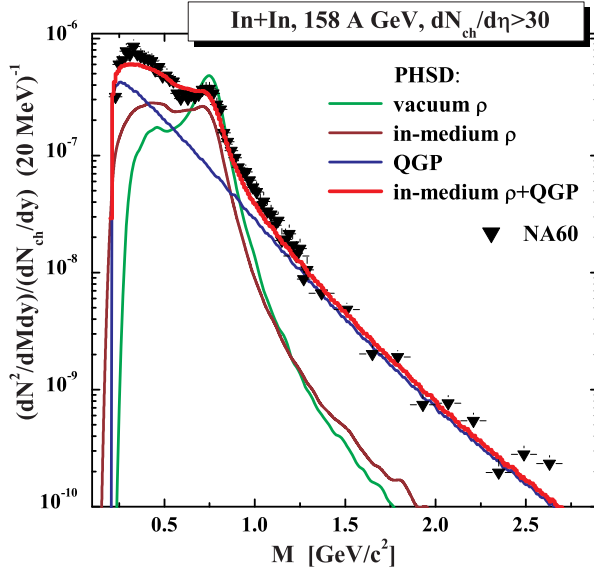


Figure 1: Acceptance corrected mass spectra of the excess dimuons from $In + In$ at 158 A GeV from PHSD compared to the data of NA60 [14]. The green dash-dotted line shows the dilepton yield from the vacuum ρ meson. The blue dashed line is the contribution to the dilepton yield from the in-medium ρ with broadened spectral function. Red solid line presents the sum of the in-medium ρ and QGP dilepton radiation (the latter is calculated in the on-shell approximation).

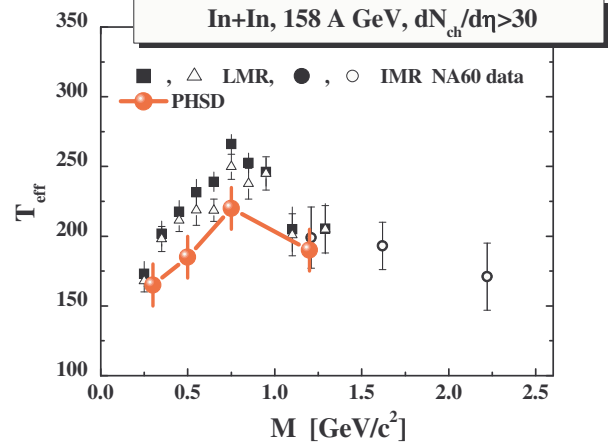


Figure 2: The inverse slope parameter T_{eff} of the dimuon yield from $In+In$ at 158 A-GeV as a function of the dimuon invariant mass in PHSD compared to the data of the NA60 Collaboration [13, 14].

interacting quark-gluon plasma (sQGP) are massive and off-shell quasi-particles (quarks and gluons) with broad spectral functions. In order to address the electromagnetic radiation of the sQGP, we derived off-shell cross sections of $q\bar{q} \rightarrow \gamma^*$, $q\bar{q} \rightarrow \gamma^* + g$ and $qg \rightarrow \gamma^* q$ ($\bar{q}g \rightarrow \gamma^* \bar{q}$) reactions taking into account the effective propagators for quarks and gluons from the DQPM in [3]. Dilepton production in the QGP - as created in early stages of heavy-ion collisions - is calculated by implementing these off-shell processes into the PHSD transport approach.

In the hadronic sector PHSD is equivalent to the Hadron-String-Dynamics (HSD) transport approach [4, 5, 6] that has been used for the description of pA and AA collisions from SIS to RHIC energies and has lead to a fair reproduction of hadron abundances, rapidity distributions and transverse momentum spectra. In particular, HSD incorporates off-shell dynamics for vector mesons – according to Refs. [7] – and a set of vector-meson spectral functions [8] that covers possible scenarios for their in-medium modification. Various models predict that hadrons change in the (hot and dense) nuclear medium; in particular, a broadening of the spectral functions or a mass shift of the vector mesons have been expected. Furthermore, QCD sum rules indicated that a mass shift may lead to a broadening and vice versa [9]; therefore both modifications should be studied simultaneously. In the off-shell transport description, the hadron spectral functions change dynamically during the propagation through the medium and evolve towards the on-shell spectral function in the vacuum.

2. Comparison to data at SPS energies

By employing the HSD approach to the low mass dilepton production in relativistic heavy-ion collisions, it was shown in [10, 11, 12] that the NA60 Collaboration data for the invariant mass spectra for $\mu^+\mu^-$ pairs from $In+In$ collisions at 158 A-GeV favored the 'melting ρ ' scenario [13, 14]. Also the data from the CERES Collaboration [15] showed a preference for the 'melting ρ ' picture. On the other hand, the dilepton spectrum from $In+In$ collisions at 158 A-GeV for $M > 1$ GeV could not be accounted for by the known hadronic sources (see Fig.2 of [10]).

The NA60 collaboration has published acceptance corrected data with subtracted charm contribution recently [14]. In Fig. 1 we present PHSD results for the dilepton spectrum excess over the known hadronic sources as produced in

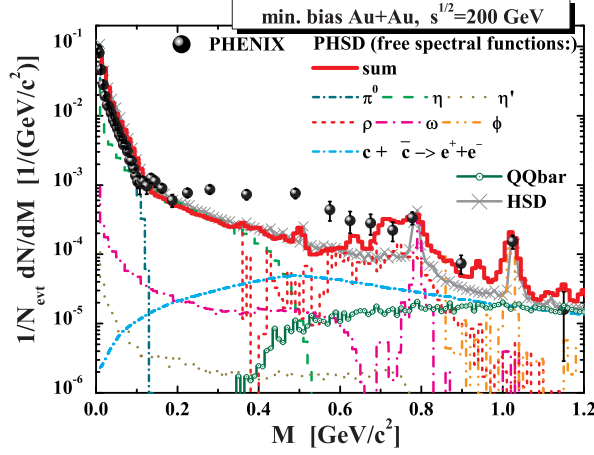


Figure 3: The PHSD results for the mass differential dilepton spectra in case of inclusive $Au+Au$ collisions at $\sqrt{s}=200$ GeV in comparison to the data from PHENIX [17] in the mass region $M=0-1.2$ GeV. The HSD results are shown by the grey line with cross symbols.

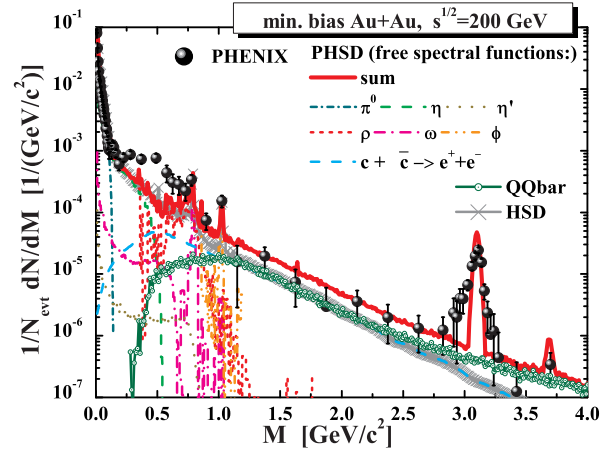


Figure 4: The PHSD results for the mass differential dilepton spectra in case of inclusive $Au+Au$ collisions at $\sqrt{s}=200$ GeV in comparison to the data from PHENIX [17] for $M=0-4$ GeV. For comparison, the HSD results are shown by the grey line with cross symbols.

$In + In$ reactions at 158 AGeV compared to the acceptance corrected data. The calculation in the PHSD approach confirms the earlier finding in a hadronic model that the NA60 data favor the scenario of the in-medium broadening of vector mesons [11]. Additionally, the yield at masses close to 1 GeV is reproduced by taking into account the dilepton production from partonic channels in the QGP. We find that the spectrum at invariant masses below 1 GeV is well reproduced by the ρ meson yield, if a broadening of the meson spectral function in the medium is assumed. On the other hand, the spectrum at $M > 1$ GeV is shown to be dominated by the partonic sources.

Moreover, accounting for partonic dilepton sources allows to reproduce in PHSD the effective temperature of the dileptons (slope parameters) in the intermediate mass range [11], see Fig. 2. On the other hand, most hadronic models do not explain the softening of the m_T distribution of dileptons for $M > 1$ GeV [13]. The softening of the transverse mass spectrum with growing invariant mass implies that the partonic channels occur dominantly before the collective radial flow has developed.

3. Comparison to data at RHIC energies

The PHENIX Collaboration has presented dilepton data from pp and $Au+Au$ collisions at Relativistic-Heavy-Ion-Collider (RHIC) energies of $\sqrt{s}=200$ GeV [16, 17] which show a large enhancement in $Au+Au$ reactions (relative to scaled pp collisions) in the invariant mass regimes from 0.15 to 0.6 GeV and from 1 to 4 GeV [18, 19]. We recall that HSD provides a reasonable description of hadron production in $Au+Au$ collisions at $\sqrt{s}=200$ GeV [20]. Whereas the total dilepton yield is quite well described in the region of the pion Dalitz decay as well as around the ω and ϕ mass, HSD clearly underestimates the measured minimum bias spectra in the regime from 0.2 to 0.6 GeV by approximately a factor of 5. Between the ϕ and J/Ψ peaks, the HSD results underestimate the PHENIX data by approximately a factor of two.

When including the in-medium modification scenarios for the vector mesons, we achieve a sum spectrum which is slightly enhanced compared to the 'free' scenario. However, the low mass dilepton spectra from $Au+Au$ collisions at RHIC (from the PHENIX Collaboration) are clearly underestimated in the invariant mass range from 0.2 to 0.6 GeV in the 'collisional broadening' scenario as well as in the 'dropping mass + collisional broadening' model. We mention that HSD results for the low mass dileptons are very close to the calculated spectra from van Hees and Rapp as well as Dusling and Zahed [21] (cf. the comparison in Ref. [22]). At higher masses (from 1 to 4 GeV) the only hadronic sources of correlated lepton pairs are the charmed mesons: semi-leptonic decays of correlated D-mesons and the dilepton decays of charmonia.

By implementing the off-shell partonic dilepton production processes into the PHSD transport approach, we calculate the dilepton spectra in $Au+Au$ at $\sqrt{s}=200$ GeV and compare to the PHENIX data in Figs. 3 and 4. In Fig. 3

we present our results for low masses ($M = 0 - 1.2$ GeV); in this region, the yield in PHSD is dominated by hadronic sources and essentially coincides with the HSD result. There is a discrepancy between the PHSD calculations and the data in the region of masses from 0.2 to 0.6 GeV. The discrepancy is not amended by accounting for the radiation from the QGP, since the latter is subleading relative to the radiation from hadrons integrated over the evolution of the collision.

In Fig. 4, the partonic radiation is visible in the mass region $M = 1 - 4$ GeV. The observed yield in the mass range between the masses of the ϕ and the J/Ψ mesons is accounted for by the sum of the dileptons generated by the quark-antiquark annihilation in the sQGP and the charmed meson decays. For $M > 2.5$ GeV the partonic yield dominates over the contribution of the (partially correlated) D-meson decays.

4. Summary

The Parton-Hadron-String Dynamics (PHSD) transport approach incorporates the relevant off-shell dynamics of the vector mesons as well as the explicit partonic phase in the early hot and dense reaction region. By comparing the dilepton spectrum calculated in PHSD to the data of the NA60 and PHENIX Collaborations, we study the relative importance of different dilepton production mechanisms and point out the regions in phase space where partonic channels are dominant.

A comparison of the transport calculations to the data of the NA60 Collaborations points towards a ‘melting’ of the ρ -meson at high densities, i.e. a broadening of the vector meson’s spectral function. On the other hand, the spectrum for $M > 1$ GeV is shown to be dominated by the partonic sources.

The low mass dilepton spectra from $Au + Au$ collisions at RHIC (from the PHENIX Collaboration) are clearly underestimated by the hadronic channels in the invariant mass range from 0.2 to 0.6 GeV. The discrepancy is not amended by accounting for the radiation from the QGP, since the latter is subleading relative to the radiation from hadrons integrated over the evolution of the collision.

In contrast, the partonic radiation is visible in the mass region $M = 1 - 4$ GeV. The dileptons generated by the quark-antiquark annihilation in the sQGP constitute about half of the observed yield in the mass range between the masses of the ϕ and the J/Ψ mesons. For $M > 2.5$ GeV the partonic yield even dominates over the D-meson contribution. Thus, accounting for partonic radiation in PHSD fills up the gap between the hadronic model results [10, 18] and the data for $M > 1$ GeV.

Work supported in part by the HIC for FAIR framework of the LOEWE program and by DFG.

References

- [1] W. Cassing and E. L. Bratkovskaya, *Phys. Rev. C* **78** (2008) 034919, *Nucl. Phys. A* **831** (2009) 215.
- [2] W. Cassing, *Nucl. Phys. A* 791 (2007) 365; *ibid.* A 795 (2007) 70.
- [3] O. Linnyk, arXiv:1004.2591, *J. Phys. G*, in print.
- [4] W. Cassing, E. L. Bratkovskaya, *Phys. Rept.* **308** (1999) 65.
- [5] E. L. Bratkovskaya, W. Cassing, *Nucl. Phys. A* **619** (1997) 413.
- [6] W. Ehehalt, W. Cassing, *Nucl. Phys. A* **602** (1996) 449.
- [7] W. Cassing, S. Juchem, *Nucl. Phys. A* **665** (2000) 377; *ibid.* A **672** (2000) 417.
- [8] E. L. Bratkovskaya, W. Cassing, *Nucl. Phys. A* **807** (2008) 214.
- [9] J. Ruppert, T. Renk and B. Müller, *Phys. Rev. C* 73 (2006) 034907.
- [10] E. L. Bratkovskaya, W. Cassing and O. Linnyk, *Phys. Lett. B* **670** (2009) 428.
- [11] O. Linnyk, E. L. Bratkovskaya and W. Cassing, *Nucl. Phys. A* **830** (2009) 491C.
- [12] O. Linnyk, E. L. Bratkovskaya and W. Cassing, *J. Phys. G* **37** (2010) 094039.
- [13] R. Arnaldi et al., NA60 Collaboration, *Phys. Rev. Lett.* **96** (2006) 162302; J. Seixas et al., *J. Phys. G* **34** (2007) S1023; S. Damjanovic et al., *Nucl. Phys. A* **783** (2007) 327c.
- [14] R. Arnaldi et al., NA60 Collaboration, *Eur. Phys. J. C* **59** (2009) 607.
- [15] D. Adamova et al. CERES Collaboration, *Nucl. Phys. A* **715** (2003) 262; *Phys. Rev. Lett.* **91** (2003) 042301; G. Agakichiev et al., *Eur. Phys. J. C* **41** (2005) 475; D. Adamova et al. *Phys. Lett. B* **666** (2008) 425; A. Marin et al.; Proceedings of CPOD07, PoS 034 (2007).
- [16] A. Adare et al., PHENIX Collaboration, *Phys. Lett. B* **670** (2009) 313.
- [17] A. Toia et al., PHENIX Collaboration, *Nucl. Phys. A* **774** (2006) 743; *Eur. Phys. J.* **49** (2007) 243; S. Afanasiev et al., PHENIX Collaboration, arXiv:0706.3034 [nucl-ex]; A. Adare et al., PHENIX Collaboration, *Phys. Rev. C* **81** (2010) 034911.
- [18] J. Manninen, E. L. Bratkovskaya, W. Cassing and O. Linnyk, arXiv:1005.0500 [nucl-th].
- [19] O. Linnyk, E. L. Bratkovskaya and W. Cassing, AIP Conf. Proc. **1257**, 700 (2010).
- [20] E. L. Bratkovskaya, W. Cassing, H. Stöcker, *Phys. Rev. C* **67** (2003) 054905; E. L. Bratkovskaya et al. *Phys. Rev. C* **69** (2004) 054907.
- [21] K. Dusling and I. Zahed, *Nucl. Phys. A* **825** (2009) 212.
- [22] A. Toia, *J. Phys. G* **35** (2008) 104037.